RAPID IN-SITU SHEAR TESTING OF ASPHALT PAVEMENTS FOR RUNWAY CONSTRUCTION QUALITY CONTROL AND ASSURANCE

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Abstract

In Canada, almost all airport runways have been constructed or rehabilitated with hot mix asphalt concrete based on cost, performance and speed of construction considerations. As with highway pavements, permanent deformation through heavy (aircraft) traffic then becomes a major concern to airport authorities, who cannot afford premature failure of runway pavements.

In cooperation with the United States Transportation Research Board and the Ontario Ministry of Transportation, researchers at Carleton University in Ottawa, Canada have developed the In-Situ Shear Stiffness Test (InSiSST™) – a new test facility for measuring shear properties of compacted asphalt concrete layers in the field. The ability to rapidly measure in-situ pavement properties immediately after construction is particularly beneficial to airport applications, as the runway may be re-opened to aircraft quickly, with confidence that the pavement will perform as expected.

A brief introduction to the InSiSST™ facility is provided, however, the primary objective of this paper is to present the results of laboratory and field testing with InSiSST™ to develop a quality control and assurance test based on fundamental shear properties. To date, these results have indicated that asphalt shear stiffness is well correlated to permanent deformation, and that a construction specification can be developed by defining threshold stiffness values. Although testing to date has been completed solely on highway asphalt pavements, the use of engineering properties such as shear stiffness and strength will allow direct applicability to airfield pavements. With continued investigation, it is anticipated that the InSiSST™ will provide a practical and rapid test for quality control and assurance of asphalt pavements, and in turn will provide significant savings through improved pavement performance and reduced delay costs.

Acknowledgements

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Introduction

Due to its enormous size and wide distribution of urban centres, air travel across Canada is vital to the rapid, efficient and safe movement of passengers and cargo. Canada's airports continue to process an increasing number of passengers and cargo with no sign of slowing in the near future. The country's busiest airport, Lester B. Pearson International Airport (LBPIA) in Toronto, Ontario observed an increase in passenger travel of 4.1% between 1999 and 2000 and now processes almost 29 million passengers and 360,000 metric tonnes of cargo per year through its four primary runways [1]. In 2000, air transport and related service industries represented $3.94 billion of Canada's Gross Domestic Product (GDP) – an increase of 6.6% since 1996 [2].

While a great many factors contribute to the operation of an airport, runway surface and structural condition are crucial toward the safe takeoff and landing of aircraft. Runway pavement designers and maintenance personnel face a daunting challenge as the large number of aircraft movements per hour (84 at LBPIA), does not allow for extended closure for maintenance and/or rehabilitation purposes. Therefore, airport pavements must be well designed and constructed to maximize service life and minimize required maintenance.

In Canada, almost every runway consists of an exposed asphalt concrete surface. Although many runways were originally constructed with Portland Cement concrete, subsequent rehabilitation has been completed using hot-mix asphalt concrete (HMAC) based on cost, performance and construction speed considerations. As with composite highway pavements, permanent deformation through heavy (aircraft) traffic then becomes a major concern to airport authorities, who cannot afford premature failure of runway pavements.

In cooperation with the United States Transportation Research Board (TRB) and the Ontario Ministry of Transportation (MTO), researchers at Carleton University in Ottawa, Canada have developed the In-Situ Shear Stiffness Test (InSiSST™) – a new field test facility for measuring shear properties of asphalt concrete layers in the field immediately after construction. Shear properties were identified by the Strategic Highway Research Program (SHRP) as being particularly important toward the resistance of asphalt pavements to permanent deformation [3].

A brief introduction to the InSiSST™ facility is provided, however, the primary objective of this paper is to present the results of laboratory and field testing with InSiSST™ to develop a quality control and assurance test based on fundamental shear properties.

Development of the In-Situ Shear Stiffness Test (InSiSST™)

Background

The concept of testing the shear strength of asphalt pavement surfaces using a modified torsion test was first conceived at Carleton University in the early 1990's [4]. The test prototype, known as the Carleton In-Situ Shear Strength Test (CISSST) derived shear properties by applying a rotational load (torque) across a steel disc affixed to the pavement surface using epoxy resin. The CISSST device is shown in Figure 1.

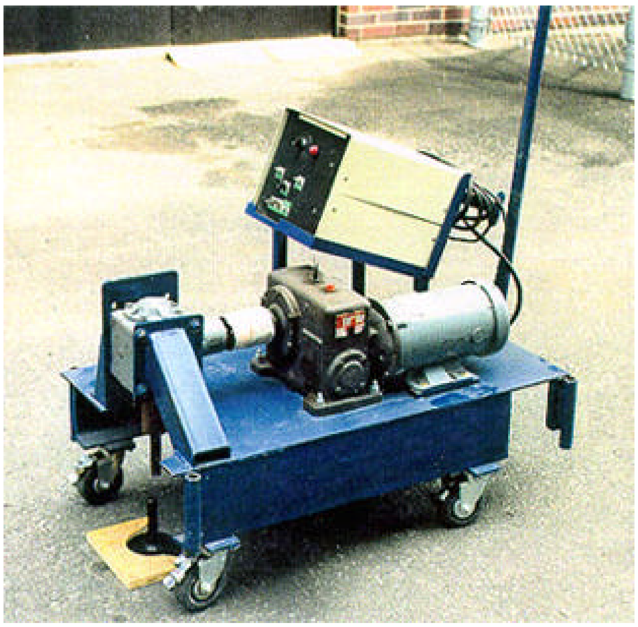

Figure 1: Carleton In-Situ Shear Strength Test (CISSST)

As shown, the CISSST incorporates an electromechanical system to develop the required torque mounted to a small cart-like chassis for manoeuvrability. A torque cell was used to connect the steel loading plate to the drive shaft and provided instantaneous torque readings during the test. The angle of twist at failure was determined using a protractor.

Unlike traditional simple shear or torsion tests, this unique loading condition (illustrated in Figure 2) required a new set of constitutive relationships between load-displacement and stress-strain to provide asphalt shear properties. For earlier investigations, the shear strength of the mix was calculated by resolving the applied torque across the failure surface, which was taken as the frustum of an inverted cone. This assumption was acceptable for comparing or ranking different mixes, which the CISSST did very well. CISSST was able to differentiate and rank the performance of different mixes, as well as the differences within the same mix placed in different geometries (curved sections vs. straight sections) [4]. However, the CISSST shear strengths were consistently greater than the laboratory results, most likely due to the contribution of the asphalt surrounding the loading disc. The following section briefly describes a new technique developed by Bekheet et al [5] involving both closed-form solutions and finite element modelling.

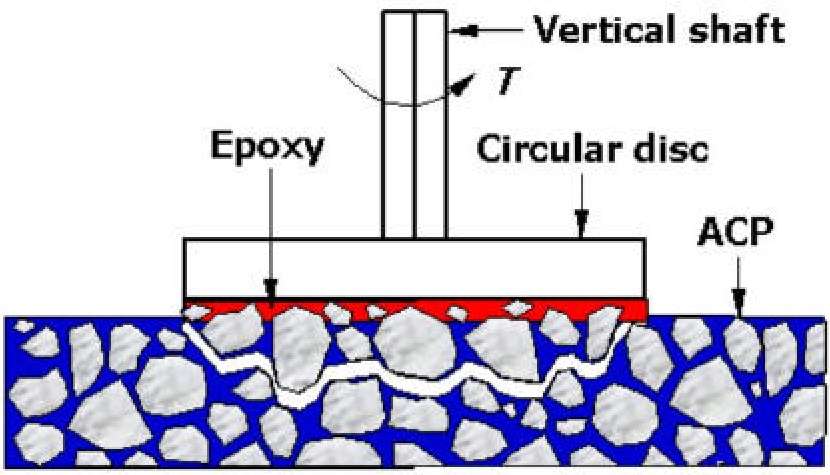

Figure 1: Modified Torsion Test for Shear Testing of Asphalt Concrete Pavements (ACP)

Improved Analytical Modelling

Given that the surface and depth of an asphalt pavement are sufficiently large in comparison with the loading disc dimensions, the pavement structure may be considered as a half-space for modelling purposes. This application of torsional moment to the surface of a half-space through a circular disc is known in the literature as the "Reissner-Sagoci Problem," first developed in the early 1940's [6]. Reissner and Sagoci showed that that for an elastic, homogeneous and isotropic material, the torsional load resulted in pure shear stresses in the radial and tangential directions ($\tau_{z\theta}$ and $\tau_{r\theta}$) using the cylindrical co-ordinates (r, θ, z) and that these stresses are a function of the circumferential displacement. All other stresses vanished under these conditions. A simple form for the shear stress $\tau_{z\theta}$ was developed for the special case at $z = 0$ (the pavement surface) and $r < a$ (under the loading disc) as shown in Equation 1.

$$t_{z?} = \frac{4 F \ G}{p \ \sqrt{\left(\frac{a}{r}\right)^2 - 1}} \qquad (1)$$

where:
G = shear stiffness of the material,
a = radius of the loading plate,
Φ = angular displacement in radians, and
r = distance from the centre of the loading area.

A relationship between the applied torque, *T*, and the resulting angular displacement was also derived as shown in Equation 2.

$$T = \frac{16}{3} G \ F \ a^3 \qquad (2)$$

Although valid only for a linear, elastic, isotropic and homogeneous materials, Equations 1 and 2 provided critical steps toward the development of a theoretically sound analytical framework for calculating in-situ shear properties of asphalt layers. The next step involved simulating the loading conditions using a finite element program. For the linear, elastic, isotropic and homogeneous material condition, the finite element mesh developed by Bekheet et al [5] was able to perfectly replicate the in-situ stresses and strains as per Equations 1 and 2. With the calibrated and verified mesh in place, future investigations will involve the introduction of (more realistic) non-linear and viscoelastic material properties to better characterize the behaviour of asphalt concrete under typical loading and environmental conditions.

Development of an Improved In-Situ Test Facility

The encouraging results obtained with the CISSST device led to the initiation of a follow-on investigation to further develop the concept of testing asphalt concrete shear properties in the field. In the spring of 1999, the National Cooperative Highway Research Program (NCHRP) awarded NCHRP-IDEA Project #55 to Carleton University under the Innovations Deserving Exploratory Analysis (IDEA) program to develop and validate a second-generation in-situ test facility. The resulting facility, known as the In-Situ Shear Stiffness Test (InSiSST™), is shown in Figure 3. Details of the InSiSST™ development effort may be found elsewhere [7], however a brief overview is appropriate.

As shown in Figure 3, the components are mounted to a small trailer to provide exceptional portability between test sites. The InSiSST™ facility utilises an electric motor and gearbox as the load cell to apply a forced circumferential displacement to a steel plate bonded to the asphalt surface. The motor and gearbox are mounted vertically on a platform attached to a positioning system that allows the platform to move both in the transverse and longitudinal directions with respect to the trailer orientation. The positioning system is mounted to a box-tube frame occupying the space between the crossbar and the axle of the trailer. The test frame is attached to the trailer frame via four jacks. During transportation of the InSiSST™, the jacks are retracted to hold the frame in the air to prevent damage. Once driven into position, the jacks are extended to lower the test frame to the ground and continue extending until the weight of the trailer is supported by the test frame, thus preventing reactionary movement of the frame while testing.

Figure 3: The In-Situ Shear Stiffness Test (InSiSST™)

The current configuration of the positioning system and test frame allows for up to five individual shear tests to be completed each time the test frame is lowered to the ground. This provides a statistically significant sample for calculation of the average shear properties of the layer. A laptop computer provides control of the test procedure and data acquisition. The test is strain controlled via a closed-loop system with instantaneous force and deformation measurements collected on the computer during the test procedure. A large plastic storage box is mounted to the front of the trailer to house the electronic components. A generator is mounted to the rear of the trailer to provide electricity for the InSiSST™, thus allowing the facility to be completely self-sufficient.

Laboratory Test Results

Two investigations completed at Carleton University to date have provided strong evidence that a quality control and assurance specification may be developed based on shear properties of asphalt mixes. The first involved laboratory torsion testing of 58 different asphalt mixes by Zahw in 1995 [8]. In addition to torsion testing, Zahw used the unconfined static creep test to estimate the permanent deformation expected for each mix using the Shell Method [9]. A comprehensive reanalysis of the resulting database by Goodman [7] derived new and powerful relationships between mix properties, shear properties, and permanent deformation estimated using the Shell Method. Of particular interest, clear relationships between rut depth from the Shell Method at three stress levels (0.1, 0.3 and 0.6 MPa, respectively) and mix shear stiffness at 25ºC were developed as illustrated in Figure 4.

Review of Figure 4 yielded much important information. First, it was clear that rutting decreases significantly with increasing mix shear stiffness – a relationship best described with power functions. For the 0.1 MPa stress level, a reduction in shear stiffness of 54% yielded an increase in rut depth of 73%. For the 0.6 MPa stress level, the effect was more pronounced as a reduction in shear stiffness of 24% yielded an increase in rut depth of 70%.

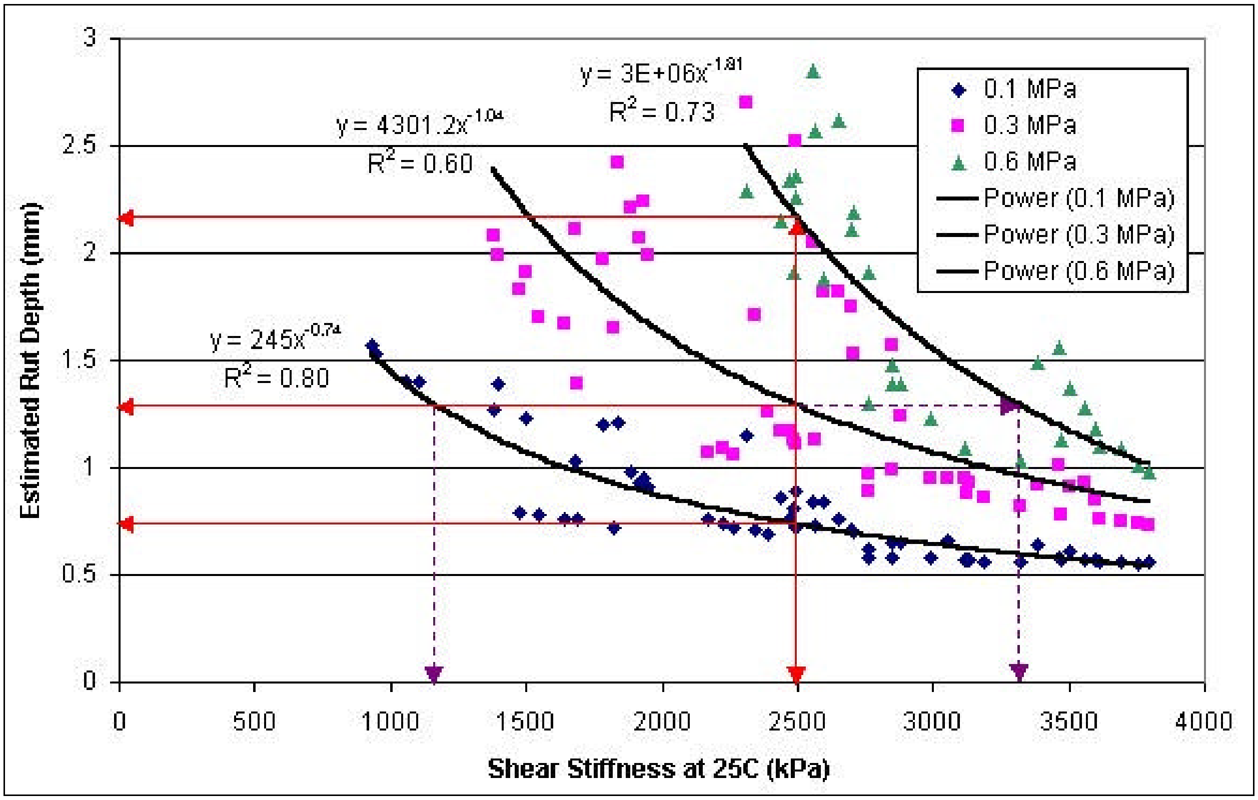

Figure 4: Relationship of Shear Stiffness to Estimated Rut Depth from Shell Method

It was further apparent that the unconfined static creep test stress level significantly affected rutting. As shown, a mix with shear stiffness of 2500 kPa could expect to experience an increase in rut depth of over 190% from the 0.1 MPa stress level to the 0.6 MPa stress level.

Field Test Results

The second investigation was completed in the field using the InSiSST™ facility at one of the Long Term Pavement Performance (LTPP) test sites in Ontario, Canada. The Petawawa test site (870900) was constructed in 1997 as part of the Specific Pavement Studies Class 9A (SPS-9A) to compare the performance of asphalt mix designed using the Superpave mix design system and performance-graded (PG) binder specification with that of conventional Marshall mix design and penetration graded binder. The as-constructed properties of the test site are provided in Table 1.

As shown, 4 of the 6 test sections were designed with the Superpave system, while 2 were Marshall mixes used by the Ontario Ministry of Transportation. Of the Marshall mixes, Section 01 incorporated an HL3 gradation with 85/100 penetration graded asphalt cement, while a polymer modified PG 58-34 asphalt cement was used for Section 62 with the HL3 gradation.

For each Superpave mix, the same 12.5mm nominal maximum aggregate size (NMAS) gradation was used, as the primary objective of the test site was to validate the low temperature PG binder specification. Furthermore, all of the PG binders selected had the same average 7-day high temperature (+58C).

Table 1: Properties of Petawawa SPS-9 Test Site

Test Section	Surface Layer Thickness		Surface Mix Type	Asphalt Binder Type	In-Situ Shear Stiffness		Total Accum. Rutting (mm)	Average Rutting Rate (mm/year)
	Mean (mm)	CoV (%)			Mean (MPa)	CoV (%)		
01	72	9	HL3	85/100 Pen	**16.66**	**8.9**	**0**	**0**
02	59	7	Superpave 12.5mm NMAS	PG 58-40 (p)	13.90	14.3	0.7	0.23
03	67	8		PG 58-34	15.93	14.4	0.3	0.1
60	67	5		PG 58-28 (p)	14.00	10.9	0.4	0.13
61	64	5		PG 58-34	*12.13*	*6.0*	*1.0*	*0.32*
62	69	8	HL3	PG 58-40 (p)	14.78	6.7	0	0

(p) indicates that the asphalt binder has been modified

According to Superpave [10], the high temperature grade is selected to minimize permanent deformation of the mix under traffic loading at the grade temperature. As such, one would expect similar performance of the test sections with respect to permanent deformation, as all would receive the same traffic loading and environmental conditioning.

Table 1 also contains in-situ shear stiffness data collected with InSiSST™ during the summer of 2000 (mean value and coefficient of variation, CoV), as well as the total accumulated rutting (mm) and average rutting rate (mm/year) observed through performance monitoring of the test sections by LTPP. Although very little rutting has been observed after 3 years in service, the InSiSST™ was sensitive to the variations in the shear stiffness of the different mixes, and accurately ranked them in terms of permanent deformation.

Figures 5 and 6 display the average rutting rate observed with the Petawawa mixes against in-situ shear stiffness, along with polynomial and power functions, respectively. The polynomial relationship (Figure 5) was first plotted as to include all of the data points from Table 1. Sections 01 and 62 were then removed in Figure 6 as their values for rutting (zero) did not permit the generation of a power function. Both functions characterized the relationship between shear stiffness and rutting rate well, with the power relationship producing a slightly stronger R^2. This result was consistent with the laboratory results, although may have been simply due to the reduced number of data points.

As with the laboratory results, both Figures 5 and 6 indicate that substantial reductions in rutting rate (67 to 75%) may be realized from modest increases in shear stiffness (21% to 25%). This observation not only promotes the use of higher quality asphalt mixes for reducing permanent deformation, but also provides great promise for the development of an advanced quality control and assurance (QC/QA) specification based on threshold shear stiffness values. Such a system would provide road authorities with a tool for assessing the quality of freshly compacted asphalt pavements against previously determined specifications to ensure maximum in-service performance.

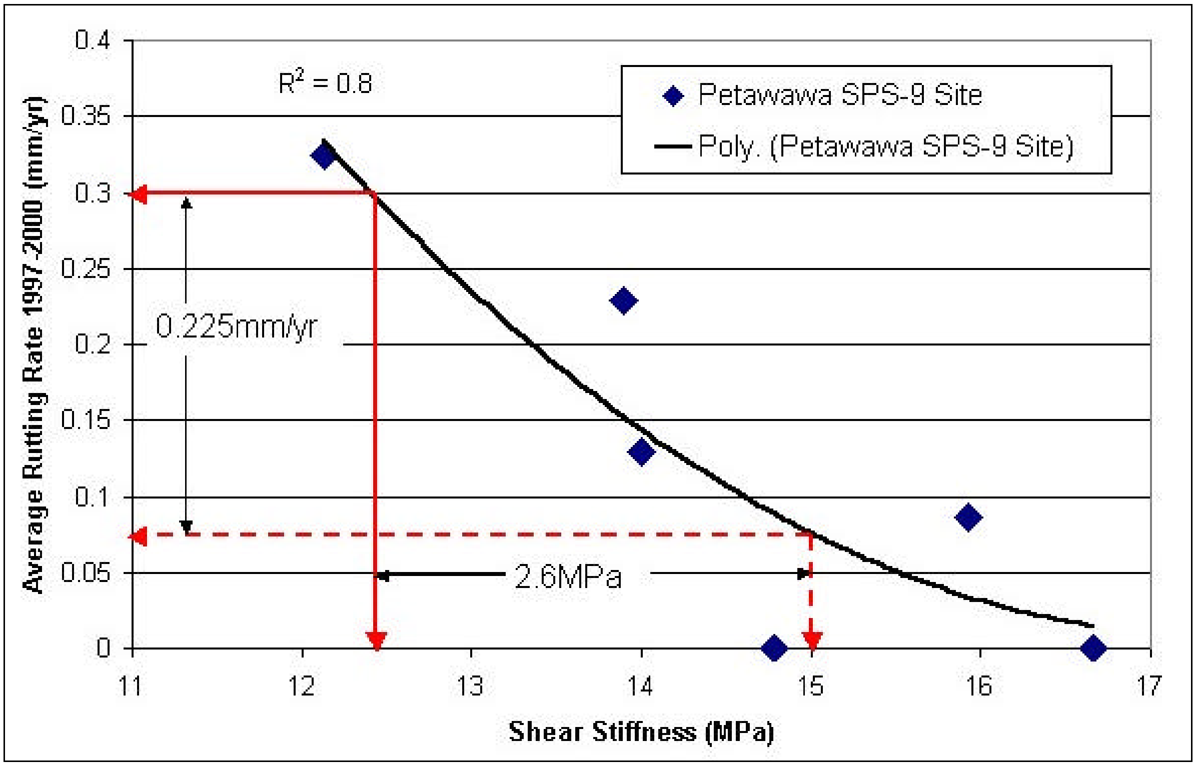

Figure 5: Shear Stiffness vs. Rutting Rate at Petawawa SPS-9 Site (Polynomial)

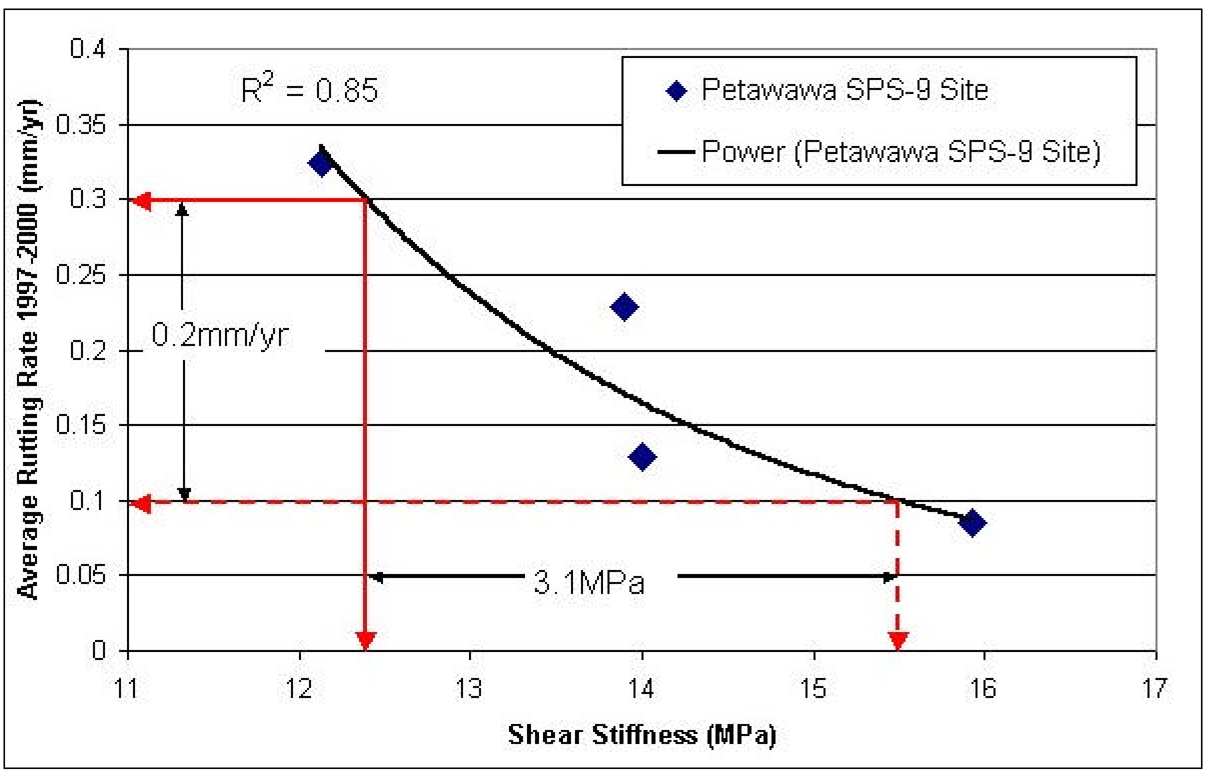

Figure 6: Shear Stiffness vs. Rutting Rate at Petawawa SPS-9 Site (Power)

Toward a Fundamentally Based QC/QA Test for Airport Pavements

Although testing to date has been completed in the laboratory and on highway asphalt pavements, the use of engineering properties such as shear stiffness and strength allows direct applicability to airfield pavements. At this time, an International Centre for Aviation Technology (ICAT) is being established at Carleton University in partnership with the Egyptian Ministry of Transport and representatives from academia, public agencies and the private sector. ICAT will initiate a research program with an emphasis on infrastructure (such as runway pavement construction), operations, communications and aerospace management [11].

The ability to rapidly measure in-situ pavement properties immediately after construction is particularly beneficial to airport applications, as the runway may be re-opened to aircraft quickly, with confidence that the pavement will perform as expected. The test method itself is virtually non-destructive and may be conducted at any location on the pavement surface (i.e. outside of the critical zone traversed by aircraft).

With continued investigation through Carleton University and ICAT, it is anticipated that InSiSST™ will provide a practical and rapid test for quality control and assurance of asphalt pavements, and in turn will provide significant savings to airport authorities through improved pavement performance and reduced delay costs.

Conclusions

The following conclusions may be drawn from the presented information:

i) The shear stiffness of hot mix asphalt concrete is well correlated to permanent deformation as tested both in the laboratory environment using the unconfined static creep test (Shell Method) and in the field using the In-Situ Shear Stiffness Test (InSiSST™).

ii) Although accumulated permanent deformation measured for the six test sections at the Petawawa SPS-9A test site between 1997 and 2000 was not large, the InSiSST™ was sensitive to changes in mix shear stiffness and accurately ranked the various mixes in terms of rutting resistance.

iii) Tests completed both in the laboratory and field indicated that modest increases in asphalt mix stiffness provide significant reductions in permanent deformation according to polynomial or power relationships.

iv) The consistent relationship between laboratory and in-situ shear stiffness with measured rutting promotes the development of a fundamentally based quality control and assurance specification for asphalt concrete pavements based on threshold values.

v) The InSiSST™ is a new and viable test facility for determining the in-situ shear properties of asphalt concrete mixes.

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